SCIENCE FOR GLASS PRODUCTION

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QUANTITATIVE CRITERIA FOR ESTIMATING GLASS VISCOSITY

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The results of a theoretical study of the quantitative estimation of glass viscosity are supplied. A new evaluation criterion, namely, dynamic coefficient of viscosity, is proposed.

One of the most important factors in the production of glass articles is the variation of glass viscosity under changing temperature. All glasses can be arbitrarily classified as "short," i.e., fast-solidifying glasses, and "long" ones that solidify slowly. For instance, continuous production of pipes, glass tubes, sheet, figured, and reinforced glass on high-efficiency lines requires fast-solidifying glass compositions. In making household glass articles of complex shapes and large sizes using extrusion, blow-molding, and blowing, glass should solidify slowly. It should be taken into account as well that hardening of glass is affected by the shape and size of the article and the initial temperature of the glass at which it is produced. Large-sized articles with a small surface area cool more slowly than similar pieces with a larger surface area. The higher the initial glass-working temperature, the faster it hardens.

It is generally accepted that the limiting values of viscosity in making glass articles are 10^2 and 10^8 Pa · sec. Therefore, the temperature interval of glass manufacture is restricted by the specified viscosity values and lies within a range from a few tens to a few hundred degrees [1, 2].

When the viscosity is approximately 10^8 Pa · sec, thin filaments can be drawn from softened glass [2]. The glass melt viscosity interval for blowing of small articles ranges from 5×10^2 to 10^5 Pa · sec, and for blowing of large articles it ranges from 5×10^2 to 10^6 Pa · sec [3]. Depending on the molding method, a glass melt drop is fed at viscosity $10^2 – 10^{3.7}$ Pa · sec [4]. The estimated data for working viscosity intervals and molding temperature intervals for the most common molding methods are given in Table 1 [5, 6].

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For quantitative description of "long" and "short" glasses, L. G. Khodskii proposed the temperature criterion of viscosity (TCV) (K^2) [7]:

$$\mathrm{TCV} = \frac{\log \eta_l - \log \eta_h}{10^7 \left(\dfrac{1}{T_h^2} - \dfrac{1}{T_l^2} \right)}, \quad (1)$$

where η_l and η_h are the viscosities at low and high values of molding temperature, respectively, Pa · sec; T_l and T_h are, respectively, the low and high values of molding temperature, K.

However, in practice there can occur instances where the temperature-viscosity parameters of glasses cannot be objectively estimated based on this criterion. For instance, "long" and "short" glasses can have equal values of TCV.

To analyzed TCV values, let us consider the temperature dependence of viscosity of several varieties of "long" and "short" glasses (Fig. 1*a* shows such a dependence in coordinates $\log \eta – T$).

TABLE 1

Molding method	Working viscosity interval, Pa · sec	Molding temperature interval, K
Drawing	$10^3 – 10^7$	973 – 1323
Rolling	$10^2 – 10^6$	1073 – 1423
Compression	$10^{2.5} – 10^{6.5}$	923 – 1323
Blowing (manual and mechanized)	$5 \times 10 – 5 \times 10^6$	1023 – 1523
Float process*	$10^3 – 10^4 – 10^7$	1323 – 1193 – 973

* Viscosity and temperature are indicated for equilibrium glass melt thickness.

TABLE 2

Glass	Temperature interval, K, for glass viscosity $10^2 - 10^8$ Pa · sec	TCV,* 10^2 K^2	DCV,* 10^2 K^2	Type of glass
1	450	98.82	26.88	"Long"
2	300	171.09	34.92	"Short"
3	460	154.87	21.74	"Long"
4	555	98.82	20.70	The same
5	370	98.82	35.93	"Short"

* For temperature interval 1073 – 1373 K

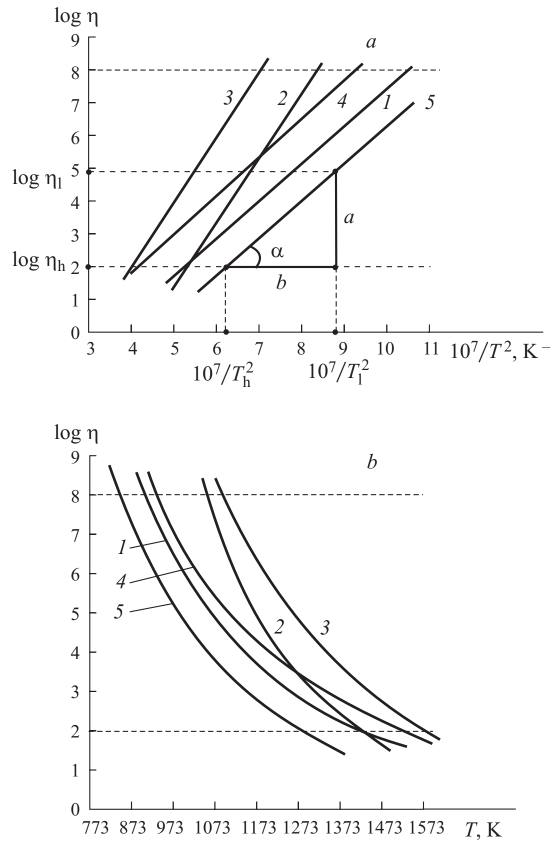

Fig. 1. Temperature dependence of glasses in coordinates log η – $10^7/T^2$ (*a*) and log η – T^2 (*b*). Curve numbers indicate glass compositions.

Glasses *1*, *3* and *4* are "long" and for viscosity $10^2 - 10^8$ Pa · sec have temperature intervals equal to 450, 460, and 555 K, respectively, whereas glasses *2* and *5* are "short" with respective temperature intervals 300 and 370 K.

To estimate the TCV, the temperature-viscosity dependence was reconstructed in the coordinates log η – $10^7/T^2$ (Fig. 1*b*). The TCV values calculated on the basis of expression (1) are shown in Table 2. It can be seen that glasses *1*, *4*, and *5* have the same TCV values, although glasses *1* and *4* are "long" and glass *5* is "short." The TCV of glass *5* determined as the ratio a ($\log\eta_l - \log\eta_h$) to $b\left(\frac{1}{T_h^2} - \frac{1}{T_l^2}\right)$ is the tangent of angle α between curve *5* and the abscissa axis (Fig. 1*b*). Since curves *1*, *4*, and *5* are inclined at the same angle, the TCV values of these glasses are the same and in this particular case equal to 98.82×10^{-2} K^2.

Considering that the TCV cannot always correctly characterize the temperature-viscosity characteristics of glasses, we have proposed the notion of the dynamic coefficient of viscosity (DCV). This parameter is considered as the temperature criterion of viscosity divided by the mean value of the viscosity logarithm for the respective temperature interval. The DCV values for the same glass composition can vary depending on the considered temperature interval, i.e., DCV = $f(\Delta T)$. Therefore, to correlate DCV values of different glass compositions, it is necessary to select the same temperature interval.

Thus, the DCV can be expressed as follows:

$$\mathrm{DCV} = \mathrm{TCV}\frac{\mathrm{TCV}}{(\log\eta_l + \log\eta_h)/2} = \frac{2\mathrm{TCV}}{\log\eta_l + \log\eta_h}. \quad (2)$$

After transformation of expression (2) we obtain

$$\mathrm{DCV} = \frac{5\times10^{-6}}{\frac{1}{T_h^2} - \frac{1}{T_l^2}}\,\frac{1-\log\eta_h/\log\eta_l}{1+\log\eta_h/\log\eta_l} = \Delta k_{\Delta T}\frac{1-m}{1+m}, \quad (3)$$

where $\Delta k_{\Delta T} = f(\Delta T)$ is the temperature interval coefficient; $m = \log\eta_h/\log\eta_l$.

TABLE 3

Temperature interval, K	Temperature interval coefficient, K^2, at its lowest temperature, K											
	873	923	973	1023	1073	1123	1173	1223	1273	1323	1373	1423
10	0.148	0.125	0.107	0.092	0.080	0.070	0.062	0.054	0.048	0.043	0.039	0.034
25	0.360	0.306	0.261	0.225	0.196	0.171	0.150	0.133	0.118	0.105	0.094	0.085
50	0.692	0.588	0.504	0.435	0.379	0.331	0.291	0.257	0.229	0.204	0.184	0.165
100	1.279	1.092	0.938	0.813	0.709	0.622	0.549	0.487	0.433	0.388	0.348	0.314
150	1.783	1.526	1.317	1.144	1.000	0.879	0.778	0.691	0.617	0.552	0.497	0.449
200	2.218	1.905	1.647	1.435	1.258	1.108	0.982	0.874	0.781	0.701	0.632	0.571
300	2.927	2.527	2.196	1.921	1.691	1.496	1.330	1.188	1.065	0.959	0.866	0.785

TABLE 4

Glass*	Weight content, %									
	SiO_2	Al_2O_3	CaO	MgO	Na_2O	K_2O	ZnO	B_2O_3	SO_3	Fe_2O_3
Sheet	72.5	1.0	9.0	3.5	14.0	–	–	–	0.40	0.050
Black marblite	65.3	2.8	6.6	–	18.5	–	–	–	–	–
Lead crystal	56.5	0.5	–	–	1.0	15.0	1.8	1.2	0.40	0.024
Household selenium ruby	66.5	1.0	–	–	13.0	6.0	8.0	3.5	0.40	0.050
Household chromium-tinted green	72.7	–	6.8	2.0	15.0	2.0	–	1.0	0.50	0.050
Pyrex chemical laboratory	79.7	2.0	0.5	0.2	3.7	1.8	–	12.1	–	–
Float glass	73.0	1.0	9.0	3.2	13.5	–	–	–	0.32	0.080

* In addition, black marblite contained 2.0% F and 4.8% Mn_2O_3, lead crystal contained 24.0% PbO, selenium ruby had 0.5% Cd and 0.5% Se, and household green had 1.0% Cr_2O_3.

TABLE 5

Glass	log η_l at temperature 873 K	Temperature interval														
		ΔT = 50 K, Δk = 0.629			ΔT = 100 K, Δk = 1.279			ΔT = 150 K, Δk = 1.783			ΔT = 200 K, Δk = 2.218			ΔT = 300 K, Δk = 2.927		
		m	$10^2 \times \frac{1-m}{1+m}$	DCV, 10^2 K^2	m	$10^2 \times \frac{1-m}{1+m}$	DCV, 10^2 K^2	m	$10^2 \times \frac{1-m}{1+m}$	DCV, 10^2 K^2	m	$10^2 \times \frac{1-m}{1+m}$	DCV, 10^2 K^2	m	$10^2 \times \frac{1-m}{1+m}$	DCV, 10^2 K^2
Lead crystal	7.85	0.873	6.78	4.26	0.771	12.93	16.54	0.702	17.51	31.22	0.631	22.62	50.17	0.500	33.33	97.57
Household selenium ruby	8.32	0.865	7.24	4.55	0.769	13.06	16.70	0.678	19.19	34.21	0.607	24.46	54.24	0.468	36.24	106.07
Household chromium-tinted green	8.69	0.854	7.87	4.95	0.762	13.51	17.28	0.664	20.19	36.00	0.595	25.39	56.32	0.466	36.43	106.62
Sheet	10.55	0.810	10.50	6.60	0.659	20.55	26.29	0.559	28.29	50.44	0.445	38.41	85.19	0.362	46.84	137.11
Pyrex chemical laboratory	12.31	0.836	8.93	5.62	0.751	14.22	18.19	0.658	20.62	36.77	0.570	27.39	60.75	0.421	40.75	119.26
Float glass	10.05	0.823	9.71	6.11	0.725	15.94	20.39	0.612	24.07	42.92	0.538	30.04	66.63	0.383	44.61	130.58
Black marblite	9.32	0.847	8.28	5.21	0.758	13.77	17.61	0.661	20.41	36.37	0.588	25.94	57.55	0.460	36.99	108.26

The coefficient of the molding temperature interval depends both on the lowest temperature at which the DCV is calculated and on the value of the temperature interval. The estimated values of $\Delta k_{\Delta T}$ for the molding temperature intervals 873 – 1473 K are indicated in Table 3. According to the data in Table 3, it is recommended to select the viscosity logarithm at high and low temperature values in the following temperature intervals: 10, 25, 50, 100, 150, 200, and 300 K.

It is convenient to calculate the DCV from expression (3), since a particular value can be determined knowing only one parameter (m) equal to the ratio of the viscosity logarithm taken at high and at low temperatures. Thus, to estimate the DCV of glasses *1 – 5* at the initial molding temperature 1073 K for the interval 1073 – 1373 K (or 300°C), the temperature coefficient interval was chosen equal to 1.691 (Table 3).

The DCV values calculated based on expression (3) are given in Table 2. The "long" glasses *1*, *3*, and *4* have lower DCV values than those of the "short" glasses. These values for the temperature interval 300 K are equal to 26.88×10^{-2}, 21.74×10^{-2}, and 20.70×10^{-2} K^2, respectively. The DCV values for "short" glasses *2* and *5* are 34.92×10^{-2} and 35.93×10^{-2} K^2, respectively. Using estimation expression (3), "long" and "short" glasses can be satisfactorily identified quantitatively.

The following glasses were selected for studies: household chromium-tinted green, household selenium ruby, lead crystal, sheet glass, chemical laboratory glass, and black marblite (Table 4). The viscosity of the glasses was determined using the known methods for the temperature intervals 873 – 1423 K [8]. These data were the initial data for DCV calculation.

Table 5 shown the data for estimating DCV for the temperature intervals 50, 100, 150, 200, and 300 K at the initial temperature 873 K. The values of the temperature interval coefficient at 873 K were taken from Table 3.

An analysis of the obtained data shows that sheet and chemical laboratory glasses have higher DCV values than lead crystal, black marblite, and household glasses. This agrees well with the working parameters of all considered glasses. Thus, chromium-tinted household green glass, selenium ruby household glass, and black marblite, which are used to make both large and small articles of different thickness and complex shapes, are "long glasses." Sheet glass and

chemical laboratory glass requiring fast hardening in the course of production belong to “short” glasses.

Thus, the proposed dynamic coefficient of viscosity is recommended for the quantitative estimation of “long” and “short” glasses.

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